REPORT 1285

SUMMARY OF DERIVED GUST VELOCITIES OBTAINED FROM MEASUREMENTS WITHIN THUNDERSTORMS [1]

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SUMMARY

This report presents the available data on the derived gust velocities in thunderstorms for altitudes up to 34,000 feet. The gust-velocity measurements were obtained from investigations made by the National Advisory Committee for Aeronautics in the vicinity of Langley Field, Va., in 1941 and 1942 and from the operations of the thunderstorm project in 1946 and 1947. The derived gust velocities were obtained from the previously evaluated effective gust velocities through use of a conversion factor that is a function of airplane characteristics and altitude. The results indicate that the intensity of the derived gust velocities in thunderstorms is essentially constant for altitudes up to about 20,000 feet and that an approximate 10-percent reduction in the intensity occurs as altitude is increased from 20,000 to 30,000 feet. These results apply to the data available for both convective and frontal types of storms.

INTRODUCTION

A revised gust-load formula with a new gust or alleviation factor (ref. 1) has been adopted for use in gust studies in order to account, in part, for the variations with altitude of the airplane response to gusts. The new gust factor is based on airplane mass ratio and on a gust profile represented by a one-minus-cosine curve whereas the previous alleviation factor was based on airplane wing loading and on a linear-gradient gust profile. The gust velocities obtained in evaluating flight measurements of the airspeed and vertical acceleration of an airplane by use of the revised formula are called the derived gust velocities and correspond to the maximum equivalent velocity for the assumed gust profile; the gust velocities previously obtained, the so-called effective gust velocities, represented only a fraction of this velocity. The derived gust velocities are accordingly numerically larger for the same turbulence than the effective gust velocities. The ratio of the derived to the effective gust velocities would also differ for the same turbulence at different altitudes since the airplane mass ratio is a function of air density.

Since the revised gust-load formula is now being used in the routine evaluation of gust data, the large amounts of effective-gust-velocity data available from V–G records on civil transport airplanes from 1933 to 1950 were converted to derived gust velocities and are summarized in reference 1. Examples of the more detailed data on the derived gust velocities obtained from VGH records taken during scheduled airline operations are given in reference 2.

In addition to these data for routine airline operations, a large amount of data on the effective gust velocities is also available from special NACA flight investigations of thunderstorms. The effective gust velocities obtained from the earlier thunderstorm investigations in the vicinity of Langley Field, Va., in 1941 and 1942 are presented in reference 3. Parts of the data on the effective gust velocities obtained from the larger scale operations of the thunderstorm project in 1946 and 1947 are presented in references 3 to 8, although the complete gust data for this investigation have not been published. This report converts all the available data on the effective gust velocities in thunderstorms to derived gust velocities and summarizes the results in a form suitable for gust-load studies. In presenting the reevaluated data, particular attention is given to the question of the variation with altitude of the derived gust velocities in thunderstorms.

SYMBOLS

A	aspect ratio, b^2/S
a_n	vertical or normal acceleration, g units
b	wing span, ft
$\bar{c}$	mean wing chord, ft
g	acceleration due to gravity, ft/sec^2
K	gust alleviation factor (function of W/S)
K_g	gust factor (function of μ_g)
M	Mach number
m	slope of wing lift curve, per radian
S	wing area, sq ft
U_{de}	derived gust velocity, $\frac{2a_nW/S}{\rho_0 mV_eK_g}$, fps
U_e	effective gust velocity, $\frac{2a_nW/S}{\rho_0 mV_eK}$, fps
V_e	equivalent airspeed, fps
W	airplane weight, lb
μ_g	airplane mass ratio, $\frac{2W/S}{\rho gm\bar{c}}$
ρ	mass density of air, slugs/cu ft
ρ_0	mass density of air at sea level, slugs/cu ft

[1] Supersedes NACA Technical Note 3538 by H. B. Tolefson, 1955.

SCOPE OF DATA

The scope of the data is summarized in table I in terms of the flight miles traveled during the recording of gust data at various altitudes within thunderstorms.

Most of the thunderstorms represented by the data for the 1941–42 investigation in the vicinity of Langley Field, Va., resulted from convective activity. The bulk of these flight data recorded within the active portions of the storms was taken at altitudes from about 10,000 to 30,000 feet. For altitudes above 30,000 feet, a total of 117 flight miles was actually recorded. As indicated by the mileage values in table I, however, only 54 miles were associated with thunderstorms; the remainder represented clear-air and cirrus-cloud conditions. The data recorded during only the 54 miles of thunderstorm flying are considered in the subsequent analysis of the derived gust velocities for the highest altitudes. A considerable number of the records for altitudes below 10,000 feet were also taken in some of the lower intensities of turbulence in small cumuliform clouds or in clear air in the vicinity of these clouds, but the large variety of weather conditions represented precluded an accurate breakdown of the records to include only thunderstorms. The data for the lowest altitude range for the 1941–42 flights are accordingly biased toward the less turbulent conditions. The effective gust velocities evaluated from the flight records for this investigation are given in reference 3.

The data for the investigations in 1946 and 1947 were obtained from the operations of the thunderstorm project in Florida and Ohio (ref. 4). The thunderstorms were caused primarily by convective activity for the 1946 investigation in Florida, while squall-line and frontal-type storms were also represented by the 1947 investigation in Ohio. The records for the 1946 investigation contained a small amount of flight distance in clear-air turbulence in the immediate vicinity of the thunderstorms. For the 1947 investigation, however, only the portion of records taken within the cloud could be determined. Parts of the data on the effective gust velocities for these tests are given in references 3 to 8.

The investigations made in the vicinity of Langley Field in 1941 and 1942 as well as the operations of the thunderstorm project in 1946 and 1947 represent surveys through thunderstorms which developed to altitudes between about 25,000 feet and 45,000 feet. Although in most cases the intention was to make the surveys at the time of maximum thunderstorm intensity, all stages of cloud development are included in the tests. The results from the flights summarized in table I can be used, therefore, to give only an overall indication of the variation of the turbulence in the storms in relation to altitudes above sea level and not in relation to such factors as cloud height or the state of the physical processes within the clouds.

TABLE I

SCOPE OF DATA IN TERMS OF FLIGHT MILES TRAVELED DURING RECORDING OF GUST DATA AT VARIOUS ALTITUDES WITHIN THUNDERSTORMS

1941–42 investigation		1946 investigation		1947 investigation	
Altitude, ft	Flight miles	Altitude, ft	Flight miles	Altitude, ft	Flight miles
5,000 to 10,000	247	6,000	993	5,000	757
10,000 to 15,000	130	11,000	1,565	10,000	1,340
15,000 to 20,000	180	16,000	1,716	15,000	1,612
20,000 to 25,000	114	21,000	1,422	20,000	1,208
25,000 to 30,000	180	26,000	1,064	25,000	939
30,000 to 34,000	54				

METHOD OF CONVERSION AND RESULTS

From the definition of U_e and U_{de}, it may be seen that the two gust velocities differ only in regard to the factors K and K_g. The effective gust velocities may accordingly be converted to derived gust velocities simply by the relation

$$U_{de}=U_e\frac{K}{K_g}$$

The large number of effective gust velocities evaluated from the thunderstorm investigations were available in the form of cumulative frequency distributions of effective gust velocities above a threshold of 4 feet per second for given altitude ranges. Rather than converting the individual values of the effective gust velocity to derived gust velocities by the previous relation, the work was simplified considerably by converting the distribution for each altitude to a distribution of derived gust velocities. Check calculations indicated that this simplification introduced only very small errors in the resulting distributions of derived gust velocities. An average value of the ratio K/K_g was determined for each altitude from the values of K previously used in the evaluation of effective gust velocities and from the values of K_g computed for individual thunderstorm traverses. Minor variations occurred in the ratio K/K_g for separate traverses within a given altitude range because of slight variation in Mach number, altitude, or airplane weight; however, for both the 1941–42 and the thunderstorm-project data, the variations from the average were less than 1 percent for about 90 percent of the cases and none were greater than about 3 percent. The average values of Mach number, Mach number correction to the lift-curve slope, mass ratio, and gust factors for each altitude range are given in table II.

In the original calculations for the effective gust velocities for the 1941–42 investigation, no correction was made for the effect of compressibility on the lift-curve slope. Inasmuch as most subsequent gust work, including the evaluation of the effective gust velocities for the 1946–47 operations of the thunderstorm project, included the usual compressibility factors, this additional correction was made to the lift-curve slope for the 1941–42 data in order to place all results on a consistent basis. As noted in table II, this correction increased the lift-curve slope from 1 to 4 percent for the 1941–42 investigation for altitudes from 5,000 to 34,000 feet.

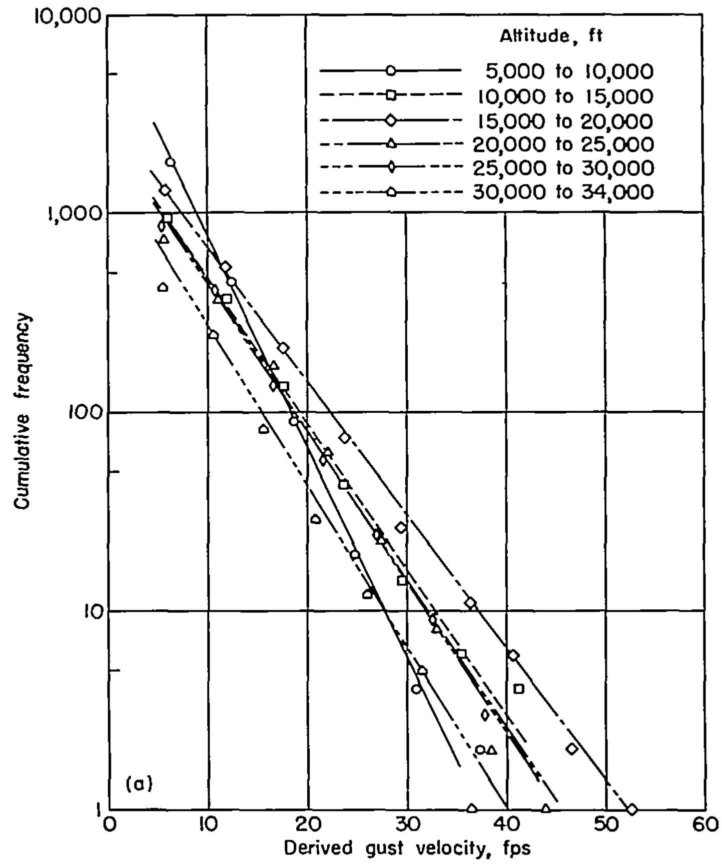
TABLE II

VALUES USED FOR CALCULATIONS

Altitude, ft	Flight Mach number	Mach number correction to lift-curve slope, $\frac{A+2}{A\sqrt{1-M^2}+2}$	Airplane mass ratio, μ_g	Gust factors		
				K_g	K	K/K_g
1941–42 investigation						
5,000 to 10,000	0.17	1.010	18.7	0.686	1.078	1.57
10,000 to 15,000	.20	1.015	23.6	.718	1.070	1.49
15,000 to 20,000	.23	1.020	27.5	.738	1.074	1.46
20,000 to 25,000	.26	1.030	32.1	.755	1.070	1.42
25,000 to 30,000	.29	1.035	37.7	.771	1.070	1.39
30,000 to 34,000	.31	1.040	44.0	.785	1.070	1.36
1946–47 investigation						
5,000 to 6,000	0.23	1.020	26.4	0.733	1.180	1.61
10,000 to 11,000	.29	1.035	30.0	.748	1.179	1.58
15,000 to 16,000	.31	1.040	34.6	.763	1.179	1.54
20,000 to 21,000	.33	1.045	41.1	.779	1.179	1.51
25,000 to 26,000	.34	1.050	48.6	.793	1.178	1.49

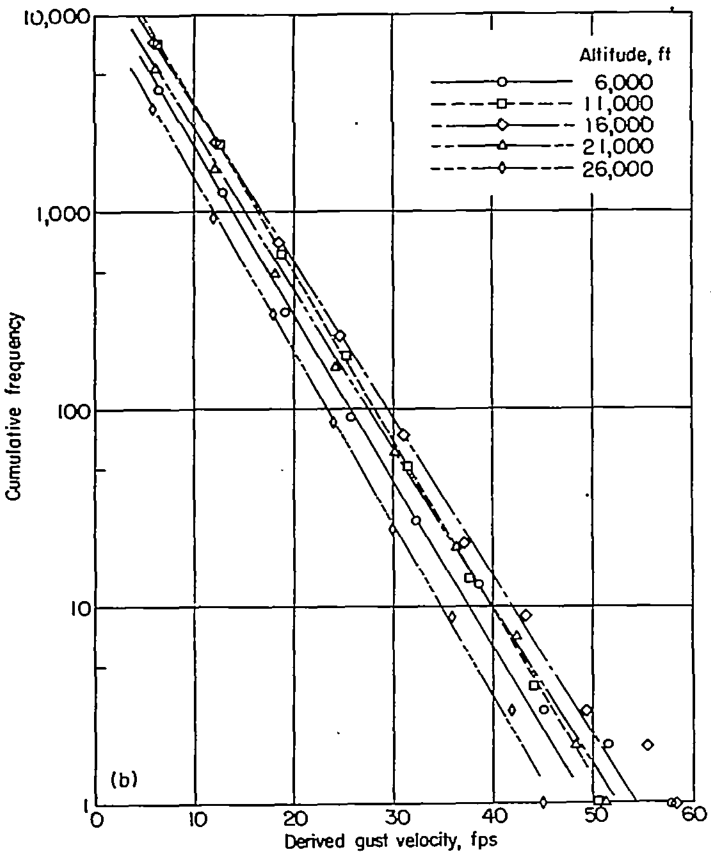
The cumulative frequency distributions of derived gust velocities are shown in figure 1 for the different altitudes of the 1941–42 investigation and the thunderstorm-project investigation. It will be noted in the figure that the gust-velocity intervals for each set of data vary somewhat between the different altitudes because of the differences in the ratio K/K_g. The dropoff in the gust frequency at the lowest gust velocity in some cases is due to incomplete evaluation of all gusts near the threshold value. Some scatter also occurs in the plotted points for the higher gust velocities at several altitudes because the infrequent encounters with the more severe turbulence result in only a small number of the larger gusts. In figure 1 (c) in particular, the scatter at the higher gust velocities for an altitude of 15,000 feet is entirely due to four gusts greater than 55 feet per second encountered during a single traverse through a thunderstorm. The trend of the data in all instances, however, is very nearly linear, and a straight line was faired through each set of data to represent the distribution. Since the bulk of the data in each case is represented by the gust velocities less than about 40 feet per second, most weight was given to these points in fairing the lines.

In order to obtain basic distributions of derived gust velocity in a form suitable for other studies, the numbers of gusts within common class intervals of 5 feet per second were obtained from the curves in figure 1. The results are tabulated in table III for the flight altitudes of each data sample. The flight mileage represented by each distribution is also given in table III for completeness.

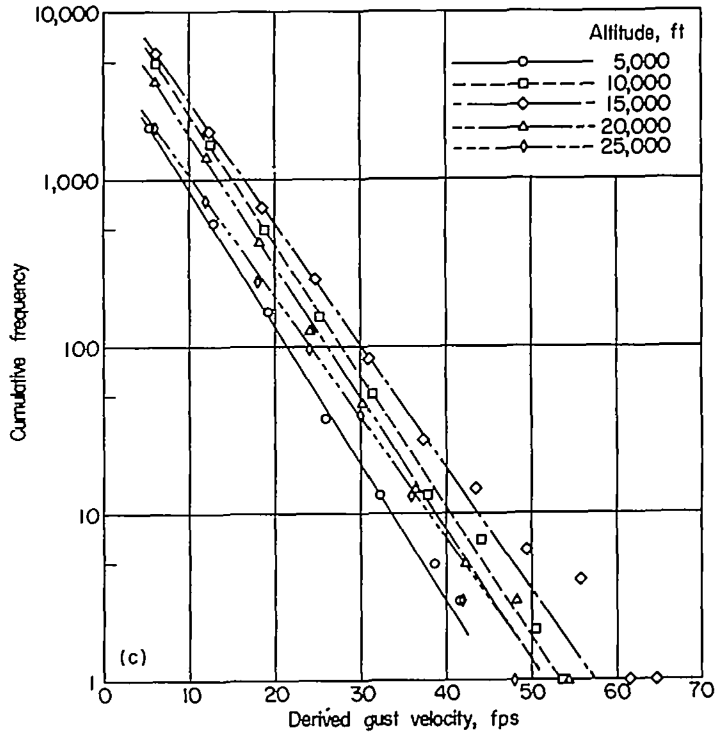


(a) 1941–42 investigation.

FIGURE 1.—Cumulative frequency distributions of derived gust velocities for thunderstorm investigations.



(b) 1946 investigation.
FIGURE 1.—Continued.



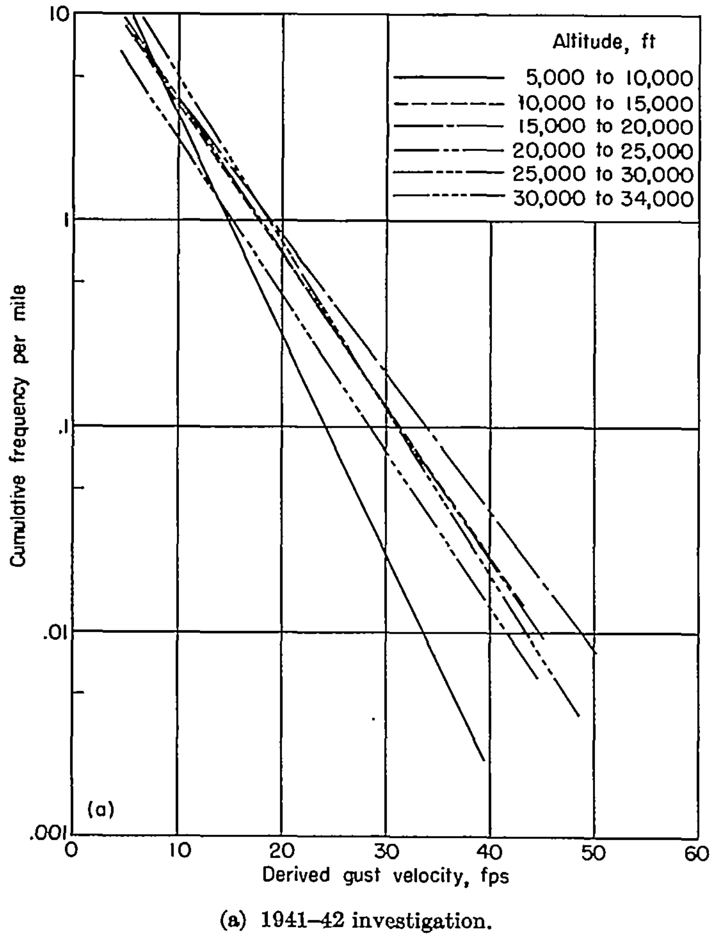
(c) 1947 investigation.
FIGURE 1.—Concluded.

TABLE III
FREQUENCY DISTRIBUTIONS OF DERIVED GUST VELOCITY.

U_{de}, fps	1941–42 investigation						1946 investigation					1947 investigation				
	Frequency of gusts at altitude (ft) of—															
	5,000 to 10,000	10,000 to 15,000	15,000 to 20,000	20,000 to 25,000	25,000 to 30,000	30,000 to 34,000	6,000	11,000	16,000	21,000	26,000	5,000	10,000	15,000	20,000	25,000
5 to 10	1, 855	635	860	570	640	410	3, 560	6, 000	5, 180	3, 920	2, 570	1, 430	3, 700	4, 000	2, 810	1, 370
10 to 15	552	283	376	249	279	171	1, 385	2, 230	2, 020	1, 590	940	510	1, 495	1, 720	1, 135	620
15 to 20	166	114	180	111	111	67	500	870	840	635	342	210	595	720	454	260
20 to 25	47	50	84	46	46	26	187	313	338	245	126	79	248	321	180	113
25 to 30	14	22	37	19	20	10	74	117	132	96	45	31	95	138	72	51
30 to 35	4	9	18	9	8	3	27	44	54	39	17	12	40	57	29	20
35 to 40	2	4	8	3	4	3	11	16	22	15	6	5	16	25	12	10
40 to 45	---	3	4	3	2	---	4	6	8	6	4	3	7	11	5	3
45 to 50	---	---	2	---	---	---	2	3	4	4	--	--	2	4	2	3
50 to 55	---	---	1	---	---	---	--	1	2	--	--	--	2	2	1	---
55 to 60	---	---	---	---	---	---	--	--	--	--	--	--	--	2	--	---
Totals	2, 640	1, 120	1, 570	1, 010	1, 110	690	5, 750	9, 600	8, 600	6, 550	4, 050	2, 280	6, 200	7, 000	4, 700	2, 450
Flight miles	247	130	180	114	180	54	993	1, 565	1, 716	1, 422	1, 064	757	1, 340	1, 612	1, 208	930

The distributions of table III or figure 1 cannot be used directly for comparing the gust velocities for the different investigations or for the different altitudes because each distribution represents a different flight mileage. In order to provide a common basis for such comparisons, the cumulative frequency distributions of figure 1 were divided by the pertinent flight mileage in table I to obtain the number of gusts greater than given values per mile of flight. These results are shown in figure 2.

As a simple measure of the relative intensity of the turbulence at the different altitudes, the gust velocity which was exceeded on the average a given number of times per mile of flight was read from figure 2 for each of the flight altitudes. A frequency level (ordinate value of fig. 2) of 0.04 gust per mile for the 1941–42 flights, 0.007 gust per mile for those of 1946, and 0.01 gust per mile for those of 1947 was selected in order to obtain derived gust velocities of about 40 feet per second for each investigation. The results are plotted at the midpoint of each altitude range in figure 3. The corresponding effective gust velocities are also shown in figure 3 for comparison. A curve has been faired through the points for the derived and effective gust velocities to indicate an estimated overall variation in these quantities with altitude. In fairing the curves, consideration was given both to the sample sizes and the conditions under which the data were taken. For example, the data point for the lowest altitude range (5,000 to 10,000 feet) for the 1941–42 investigation was disregarded because of the fairly large proportion of data taken in clear air or smaller clouds. The curves are dashed for altitudes above 28,000 feet because of the small data sample and uncertainty of the results at the highest altitude.

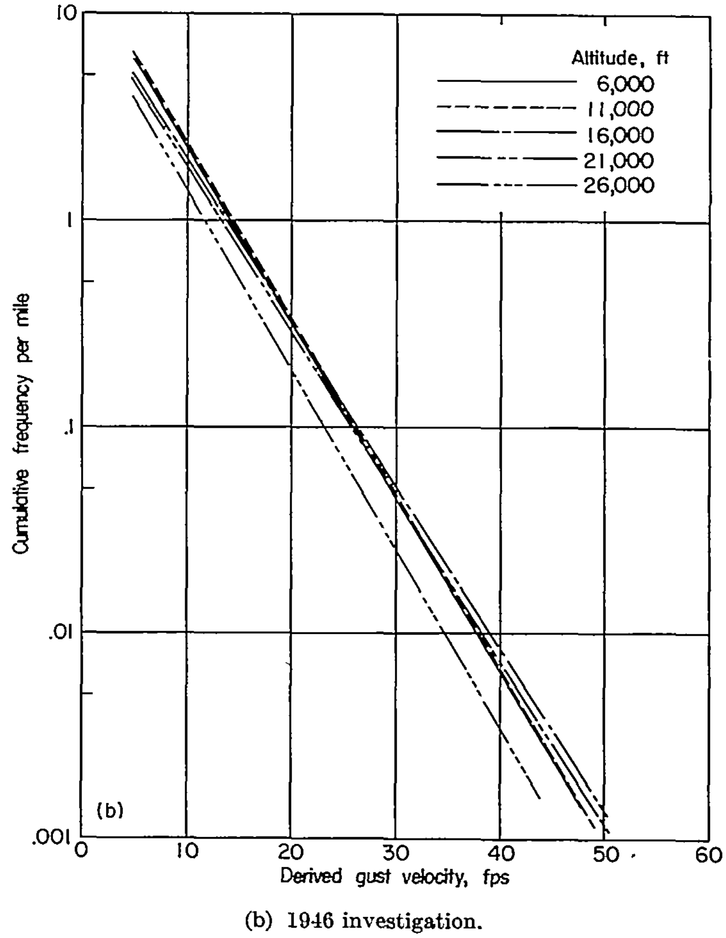


(a) 1941–42 investigation.

FIGURE 2.—Average frequency of exceeding given values of derived gust velocity per mile of flight at different altitudes within thunderstorms.

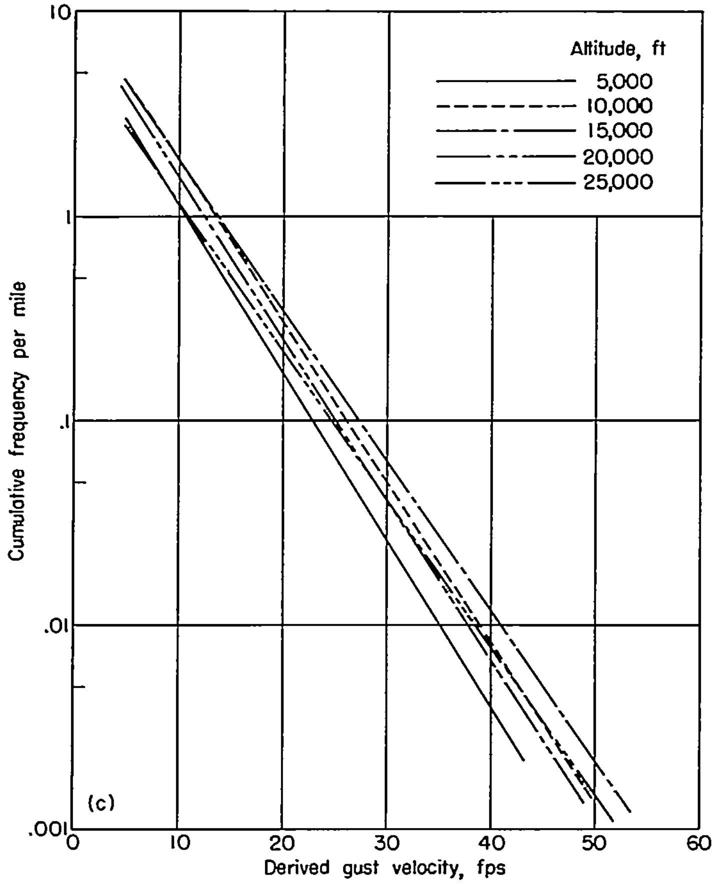
DISCUSSION

Inspection of figure 2 indicates no consistent or large variations in the magnitude of the derived gust velocities for the different altitudes of each set of data if altitudes below 10,000 feet are neglected in the 1941–42 investigation. For a frequency level corresponding to the larger gust velocities, which are of primary interest from a loads standpoint, figure 2 indicates that differences of about 5 to 7 feet per second occur in the magnitude of the derived gust velocities for the different altitudes of each investigation. A comparison of the three sets of distributions in figure 2 also indicates that the derived gust velocities for the 1946 and 1947 thunderstorm investigations were of almost equal intensity, whereas the gust velocities for the 1941–42 investigation were somewhat greater.



(b) 1946 investigation.

FIGURE 2.—Continued.



(c) 1947 investigation.
FIGURE 2.—Concluded.

In addition to the observations from figure 2 on the intensity of the turbulence at different altitudes, calculations were made to check whether the differences noted between the distributions for the separate altitudes resulted from differences in the turbulence intensities or from random or sampling fluctuations in the data. These results, based on a comparison of the confidence limits for each distribution at a gust velocity of about 40 feet per second, indicated that a scatter of only about 1 foot per second would be ascribed to sampling errors. The differences in the derived gust velocities of 5 to 7 feet per second at the different altitudes accordingly reflect the differences in the turbulence intensities.

A better indication of the magnitude of the derived gust velocities measured at the separate altitudes in thunderstorms can be seen in figure 3. Although the points scatter somewhat from altitude to altitude, the overall trend of the data indicates that the values of the derived gust velocities remain essentially constant for altitudes up to about 20,000 feet and then decrease slightly at the higher altitudes. On the basis of the faired curve in the figure, the magnitude of this decrease is from about 39 feet per second at 20,000 feet to 35 feet per second at 30,000 feet, or a decrease of approximately 10 percent in 10,000 feet. Other similar plots were made to check this variation with altitude at gust-velocity levels of about 20 and 30 feet per second. These results indicated substantially the same type of variation with altitude as shown in figure 3.

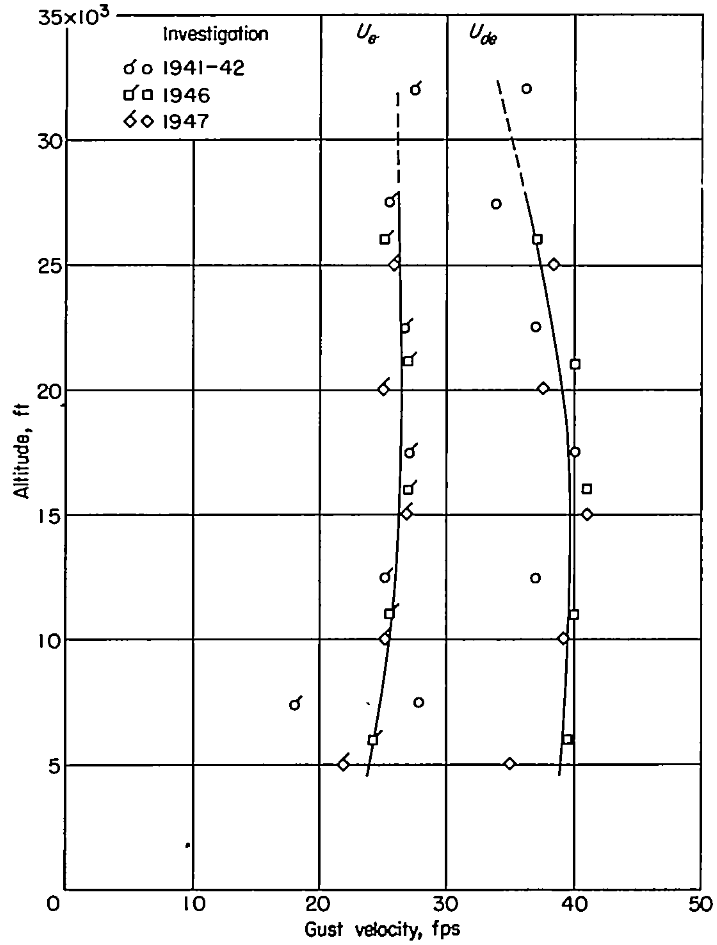


FIGURE 3.—Derived and effective gust velocities exceeded on the average a given number of times per mile of flight at various altitudes within thunderstorms.

A comparison of the derived gust velocities with the effective gust velocities in figure 3 illustrates the effect of altitude on the ratio K/K_g. It will be noted from the figure that the effective gust velocities are essentially constant with altitude, whereas the decrease in the ratio K/K_g at the higher altitudes leads to the decrease in derived gust velocities of about 10 percent from 20,000 to 30,000 feet.

In an attempt to determine whether variations existed in the turbulence intensities for different types of thunderstorms, the gust-velocity measurements taken in convective types of storms were compared with those taken in frontal types of storms for the 1947 investigation. Reference 4 indicated that five of the thunderstorms for which records were obtained in 1947 were of convective origin. Ten thunderstorms were associated with frontal activity, either squall-line or surface-front condition. A comparison of the distributions of the derived gust velocity for the convective types of storms with those for the frontal types of storms indicated only negligible differences in either the overall intensity of the turbulence or in the variation of the intensity with altitude. As has also been noted in connection with figure 2, the overall intensity of the turbulence for the convective types of storms investigated in 1946 was about equal to that for the combined convective and frontal types of storms investigated in 1947. These examinations of the

data accordingly indicated no real variations between the derived gust velocities for the two storm types.

CONCLUSIONS

A study of the available data on the derived gust velocities within thunderstorms indicates the following:

1. The intensity of the derived gust velocity which was exceeded a given number of times per mile of flight within thunderstorms remains essentially constant for altitudes up to about 20,000 feet. An approximate 10-percent reduction in the intensity of the derived gust velocities occurs as altitude is increased from 20,000 to about 30,000 feet.

2. For the convective and frontal types of thunderstorms represented by the data, no differences that could be ascribed to storm type were indicated in either the overall intensity of the turbulence or in the variation of the intensity with altitude.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *July 27, 1955.*

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